FLRPC: Proton Driver

Bob Kephart

March 24, 2004

Outline

- **FLRPC: Proton Driver Working Group**
- **Proton Driver Design Studies**
  - 8-GeV synchrotron
  - 8-GeV Superconducting Linac ← bulk of the talk
  - MI upgrades
- **FLRPC: PD recommendations**
- **Conclusions**

Studies of the FNAL Proton Source

- **Several studies have had the goal of understanding the limitations of the existing source and suggesting upgrades**
- **Proton Driver Design Study I:**
  - 16 GeV Synchrotron (TM 2136) Dec 2000
- **Proton Driver Design Study II (draft TM 2169) :**
  - ✓ 8 GeV Synchrotron May 2002
  - ✓ 2 MW upgrade to Main Injector May 2002
  - ✓ 8 GeV Superconducting Linac: Feb 2004
- **Proton Team Report (D Finley):** Oct 2003
  - **Report:** http://www.fnal.gov/directorate/program_planning/studies/ProtonReport.pdf
  - **Limitations of existing source, upgrades for a few 10's of $ M.**
  - "On the longer term the proton demands of the neutrino program will exceed what reasonable upgrades of the present Booster and Linac can accommodate → FNAL needs a plan to replace its aging LINAC & Booster with a new more intense proton source (AKA a Proton Driver)

Fermilab:Long Range Planning

- **In April of 2003 the Fermilab Director formed a committee to provide advice on the long range scientific program of the laboratory. FLRP Membership & Charge:**

  http://www.fnal.gov/directorate/Longrange/Long_rang_planning.html

- **Excerpt from the charge to the LRP committee:**
  - " I would like the Long-range Planning Committee to develop in detail a few realistically achievable options for the Fermilab program in the next decade under each possible outcome for the linear collider. …."

- **It was clear from the start that a new intense proton source to serve long baseline neutrino experiments was one such option…**

FLRP:PD Working group

Fermi National Accelerator Laboratory A Department of Energy National Laboratory
Managed by Universities Research Association

Fermilab Long Range Planning Committee
Working Groups

Physics Working Group Convenor: Chris Hill Documents	Neutrinos Working Group Convenor: Gary Feldman Documents
Linear Collider Working Group Convenor: Steve Holmes Documents	Large Hadron Collider Working Group Convenor: John Womersley Documents
Proton Driver Working Group Convenor: Bob Kephart Documents	Accelerator R&D Working Group Convenor: Steve Geer Documents
Particle Astrophysics Working Group Convenor: Josh Frieman Documents (when available)	Non-(Particle Physics) Working Group Convenor: Joel Butler Documents
Resources Working Group Convenor: Hugh Montgomery Documents (when available)	International Lab Issues Working Group Convenor: Documents (when available)

PD Subcommittee:

Bob Kephart, chair
Steve Geer
Chris Hill
Peter Meyers
Sergei Nagaitsev

Technical Advisors

Dave Finley	**Past BD Head (proton economics)**
John Marriner	**Past BD Head**
Shekar Mishra	**Past deputy head MI project**
Victor Yarba	**SCRF R&D (started TD RF group)**

Proponents

Weiren Chou	**Synchrotron based Proton Driver**
Bill Foster	**SCRF Linac based Proton Driver**

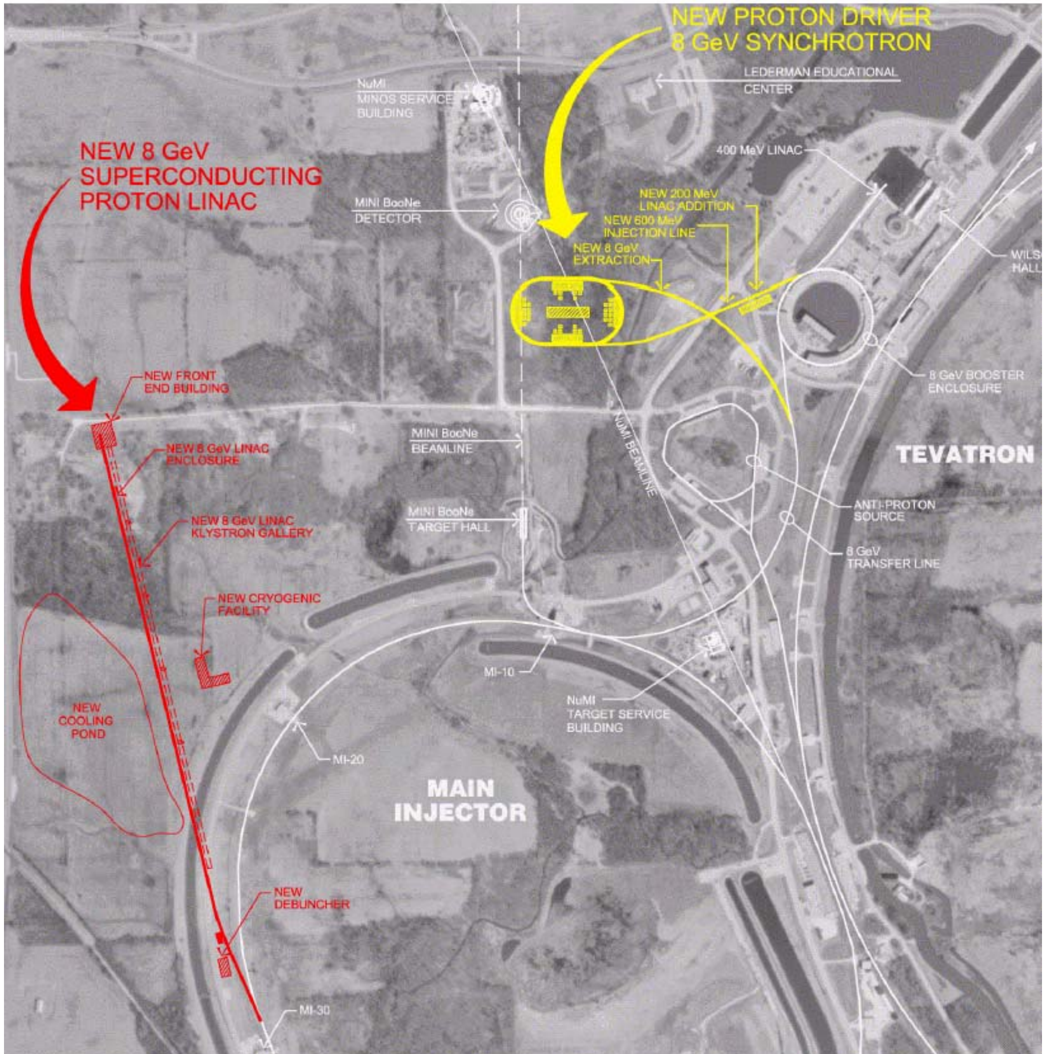
FLRP:PD Working group

- **Had a series of 14 meetings**
  - Well attended by Expert Participants
  - 27 additional people made presentations or important contributions to the meetings
  - 3 joint meetings with other LRP sub committees
- **To obtain input from the community an open session took place on Oct 9, 2003**
- **"FLRP Retreat" Jan 9-10**
  - "Draft Proton Driver Recommendations
- **Final Report and recommendations in Mar 2004**
- **PD meetings has now evolved into a regular Proton Driver R&D/Design meeting**
  - More people joining the effort

Proton Driver Design Studies

- **8 GeV Synchrotron (TM 2169)**
  - Basic plan is to replace the existing Booster with a new large aperture 8 GeV Booster (also cycling at 15 Hz)
  - Takes full advantage of the large aperture of the Main Injector
  - Goal= 5 times # protons/cycle in the MI ($3 \times 10^{13} \rightarrow 1.5 \times 10^{14}$)
  - Reduces the 120 GeV MI cycle time 20% from 1.87 sec to 1.53 sec
  - The plan also includes improvements to the existing linac (new RFQ and 10 MeV tank) and increasing the linac energy (400→600 MeV)
  - The increased number of protons and shorter cycle time requires substantial upgrades to the Main Injector RF system
- **Net result = increase the Main Injector beam power at 120 GeV by a factor of 6 (from 0.3 MW to 1.9 MW)**

PD: 8 GeV Synchrotron



- Sited West of the existing booster
- Twice the shielding of the current booster
- Large aperture magnets
- Collimators contain losses to avoid activation of equipment

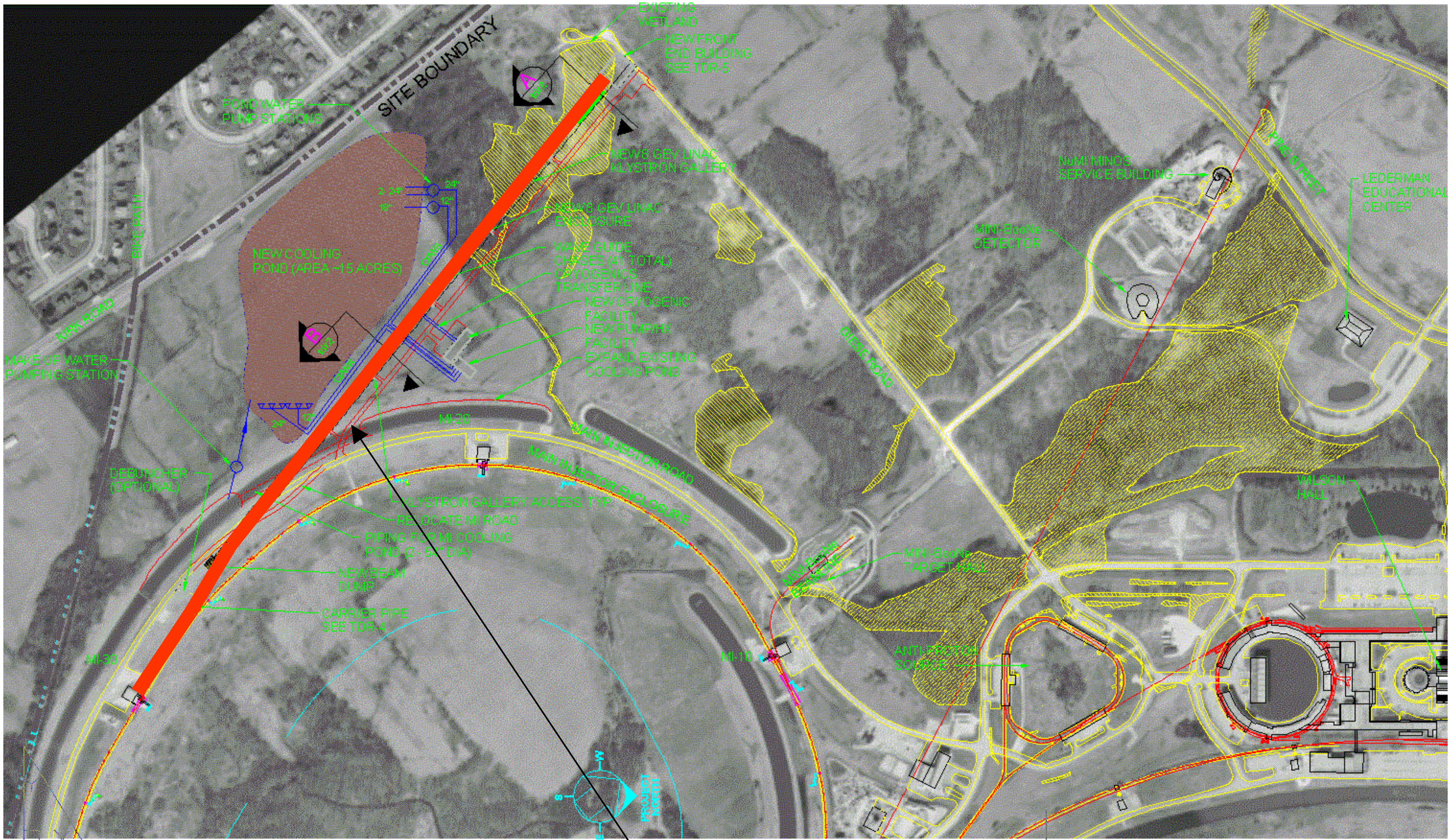
PD: 8 GeV Synchrotron

- **Synchrotron technology well understood**
  - May be cheaper than an 8 GeV linac
  - We have more experience with this kind of machine
- **But…**
  - Doesn't replace entire linac ➔ 200 MHz PA's would still be a vulnerability, aging linac equipment still an issue
  - Cycle time is still 15 Hz ➔it would still take 5/15 of a sec to fill MI with 6 booster batches➔ limits upgrades to the MI cycle time (Beam power is proportional to # p/cycle x cycles/sec)
  - Large aperture rapid cycling magnets➔development
  - Significant interruption of operations to upgrade linac and break into various enclosures (vs Run II)
  - Losses, instabilities, etc… vs ultimate performance ?

PD: 8 GeV SC Linac

- **Basic concept, design, (& slides) are due to Bill Foster at FNAL**
- **Observation: $/ GeV for SCRF has fallen dramatically → can consider a solution in which H- beam is accelerated to 8 GeV in a SC linac and injected directly into the Main Injector**
- **Why an SCRF Linac looks attractive:**
  - Many components exist (few parts to design vs new booster synchrotron)
    - Copy SNS, RIA, & AccSys Linac up to 1.2 GeV
    - Use “TESLA” Cryo modules from 1.2 → 8 GeV
  - Probably simpler to operate vs two machines (ie linac + booster)
  - Produces very small emittances vs a synchrotron
  - Delivers high beam powers simultaneously at 8 & 120 GeV
- **Injection into MI is done with 90 turns of small transverse emittance beam (2 π mm-mrad, 95% normalized) which is “phase space painted” into MI (40 π) aperture in 1 ms→ MI “fill time” that is negligible vs MI ramp times (more later)**

8 GeV Linac Siting for Design Study



- Sited tangent to the Main Injector

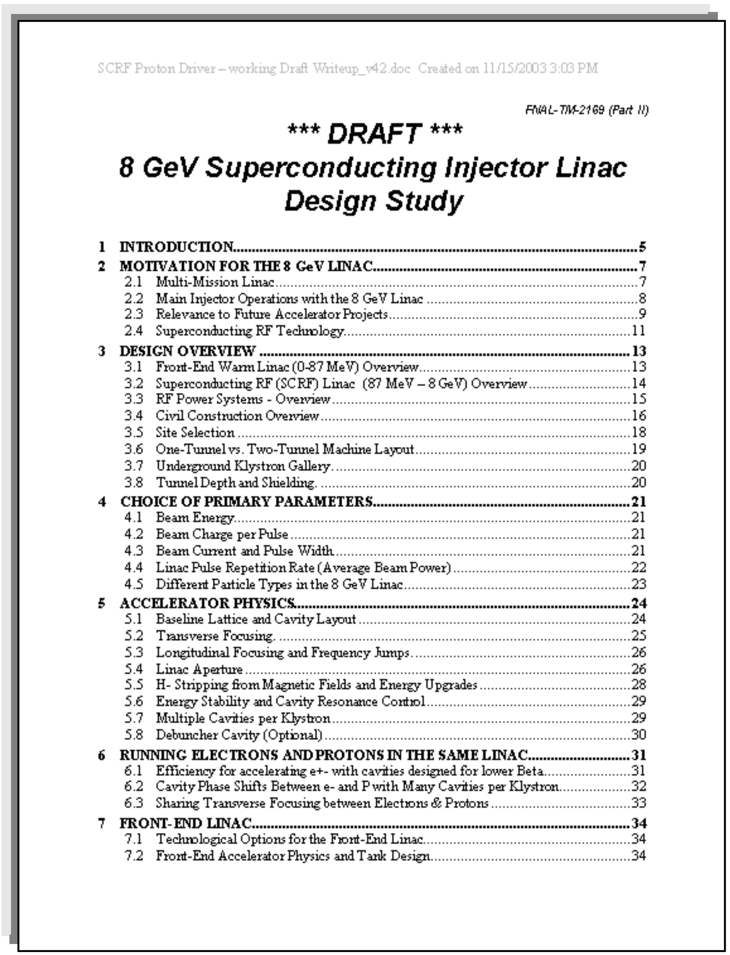
Other Possible SCRF Linac Missions

- **Principle Mission: Proton superbeams for Neutrinos**
  - 8 GeV or 120 GeV from MI (NUMI/Off-axis = NOvA)
- **Also:**
  - Protons for future 120 GeV fixed target experiments and continued anti-proton production
- **Other possibilities:**
  - Protons:
    - Could Drive a Future Neutrino Factory
    - Could Drive a Spallation Neutron source
    - Could serve as a low emittance injector to a future VLHC
  - Accelerate electrons ?
    - Could drive an x-ray FEL
    - Could be useful for LC beam or technology studies

Technological Synergies

- **Lots of labs use or plan use of SCRF**
- **This provides many opportunities for collaboration and shared infrastructure/development costs**
- **Other Accelerators:**
  - Existing: ATLAS (ANL), CBEAF, FNPL, TTF-I (DESY)
  - Construction: SNS (ORNL), DESY FEL
  - Proposed:
    - Cold Technology Linear Collider (TESLA),
    - RIA (ANL)
    - Light sources: LUX (LBNL), Cornell light source, PERL (BNL), MIT (Bates)
    - Electron cooling in RHIC (BNL), eRHIC (BNL)
    - BNL proton superbeam proposes 1.2 Gev SCRF Linac
    - SC linac is being discussed as part of the LHC upgrade
    - Medical isotope production, etc

A Draft Design Study exists



SCRF Proton Driver – working Draft Writeup_v42.doc Created on 11/15/2003 3:03 PM

FNAL-TM-2169 (Part II)

*** DRAFT ***

8 GeV Superconducting Injector Linac Design Study

- **Web Link:**

http://tdserver1.fnal.gov/project/8GeVLinac/DesignStudy/

131 page document

- **Plan: Next Few Weeks:**
  – Merge with PD II Design Study
- **Technically it looks to be feasible**
- **Principle issue is the cost**
  – SNS was very expensive but there are reasons that this was so…
  – TESLA appears to be very cheap / Gev
  – Need to do a careful Technical Design Report including optimization and costs
- **That’s the plan (more later)**

8 GeV Linac Baseline

Design Study (130 pages): http://tdserver1.fnal.gov/project/8gevlinac

- **Warm Copper DTL**
- **805 MHz SNS & RIA Cavities to 1.3 GeV**
- **Modified TESLA (1207.5 MHz) to 8 GeV**

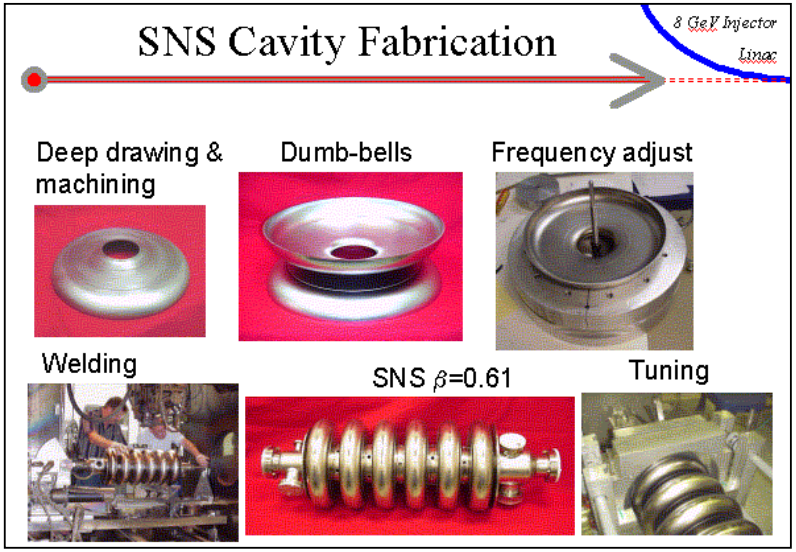
- **48 "TTF-style" Cryomodules**
- **384 Cavities (assuming TESLA-500 Gradients)**

New Technology:

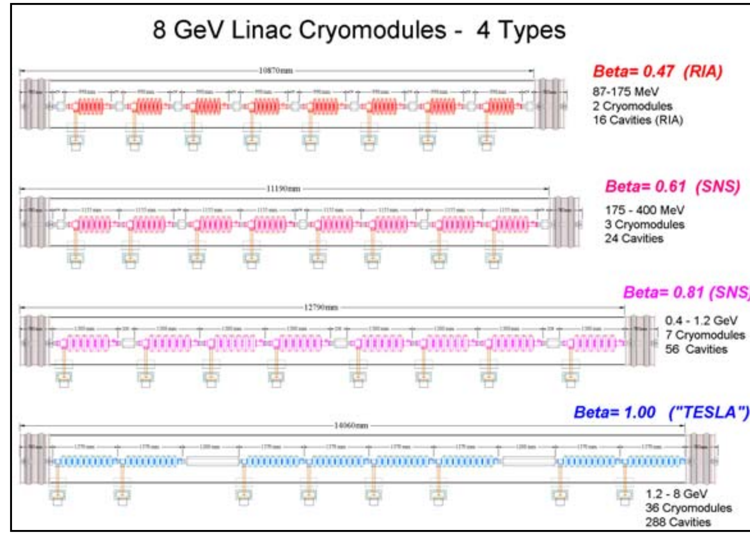
Extend TESLA RF Fan-Out to Proton/H- Linac

- ***41 Klystrons in baseline design***

Most other TECHNICAL SUBSYSTEM DESIGNS *EXIST* and have been shown to *WORK*



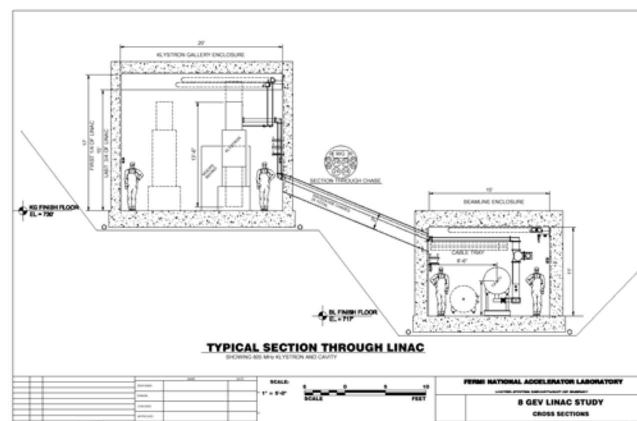
SNS Cavites



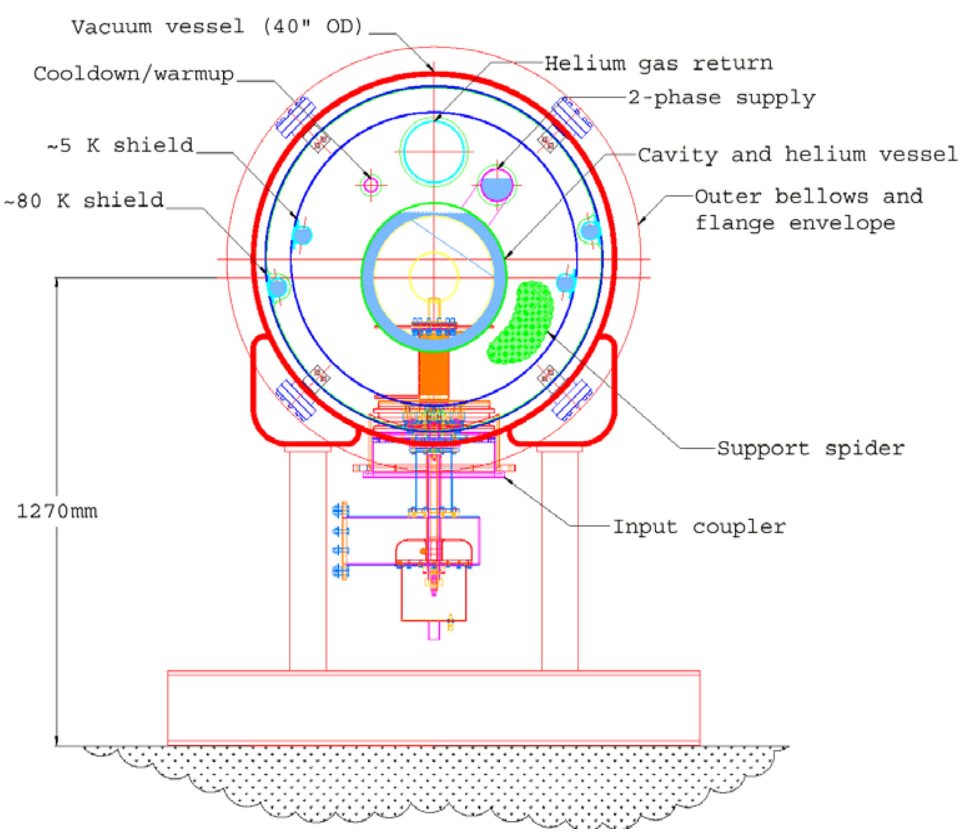
"TTF Style" Cryomodules

FNAL/TTF Modulators

Civil Const. Based on FMI



TESLA-Style Cryomodules for 8 GeV



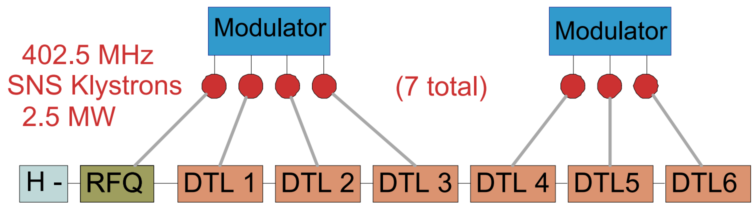
Design conceptually similar to TESLA

- No large cold gas return pipe
- Cryostat diameter ~ LHC

RF Couplers are KEK / SNS design, conductively cooled for 10 Hz operation

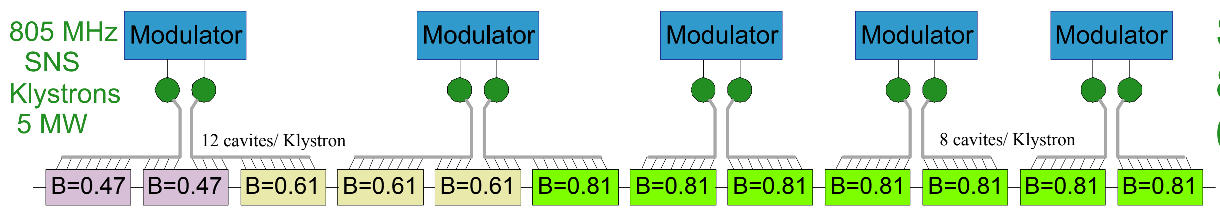
Cold string length ~ 300m vs every module in SNS => cheaper (more like TESLA)

8 GeV Linac Baseline   2 MW



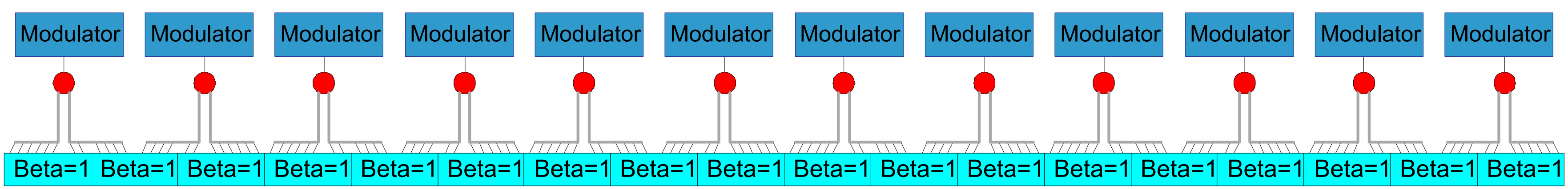
Warm Copper
Drift Tube Linac
402.5 MHz
0 - 87 MeV

8 GeV 2 MW LINAC
41 Klystrons   (3 types)
31 Modulators 20 MW ea.
7 Warm Linac Loads
48 Cryomodules
384 Superconducting Cavities



Superconducting "SNS" Linac
805 MHz
0.087 - 1.2 GeV

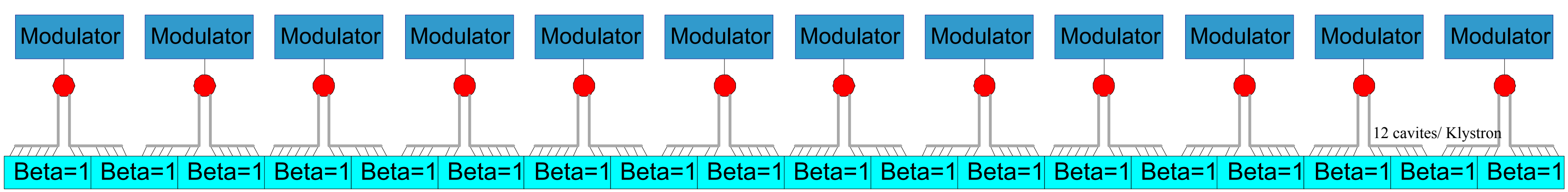
10 Klystrons
96 cavites in 12 Cryomodules



"TESLA" LINAC

1207 MHz   Beta=1

24 Klystrons
288 cavites in 36 Cryomodules



8 GeV Linac Parameters

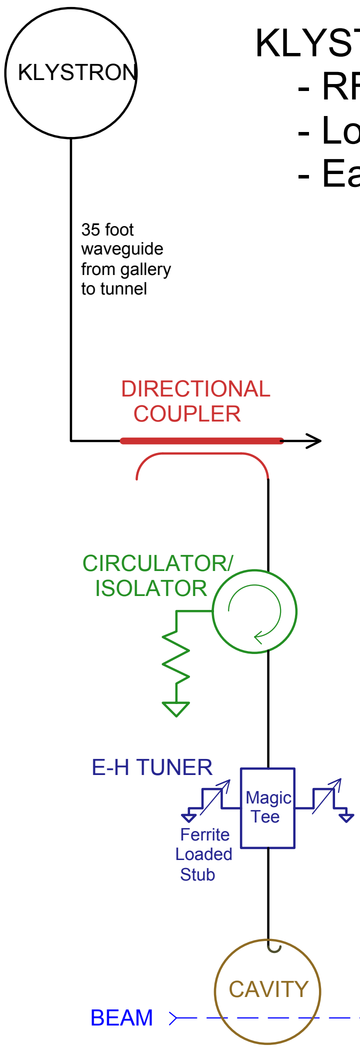
8 GeV LINAC			
Energy	GeV	8	
Particle Type	H- Ions, ~~Protons~~, or Electrons		
Rep. Rate	Hz	10	
Active Length	m	671	
Beam Current	mA	25	
Pulse Length	msec	1	
Beam Intensity	P / pulse	1.5E+14	(can be H-, P, or e-)
	P/hour	5.4E+18	
Linac Beam Power	MW avg.	2	
	MW peak	200	

MAIN INJECTOR WITH 8 GeV LINAC			
MI Beam Energy	GeV	120	
MI Beam Power	MW	2.0	
MI Cycle Time	sec	1.5	filling time = 1msec
MI Protons/cycle		1.5E+14	5x design
MI Protons/hr	P / hr	3.6E+17	
H-minus Injection	turns	90	SNS = 1060 turns
MI Beam Current	mA	2250	

RF System for 1.2→ 8 GeV Linac

- **Assumes TESLA-style RF distribution works**
  - One TESLA multi-beam Klystron per ~12 Cavities
- **Requires a "fast ferrite" E-H tuner to control the phase and amplitude to each cavity**
  - The fundamental technology is proven in phased-array radar transmitters.
  - This R&D was started by SNS but dropped due to lack of time.
  - R&D is required to optimize the design for the Linac, funding in TD FY04 budget to start this effort
  - Also needed if Linac alternates between e and P.
- **Modulators are identical to TESLA modulators**

RF Fanout at Each Cavity



KLYSTRON
- RF Power Source
- Located in Gallery above tunnel
- Each Klystron Feeds 8-16 Cavities

DIRECTIONAL COUPLER
- Picks of a fixed amount of RF power at each station
- Passes remaining power downstream to other cavities

CIRCULATOR / ISOLATOR
- Passes RF power forward towards cavity
- Diverts reflected power to water cooled load

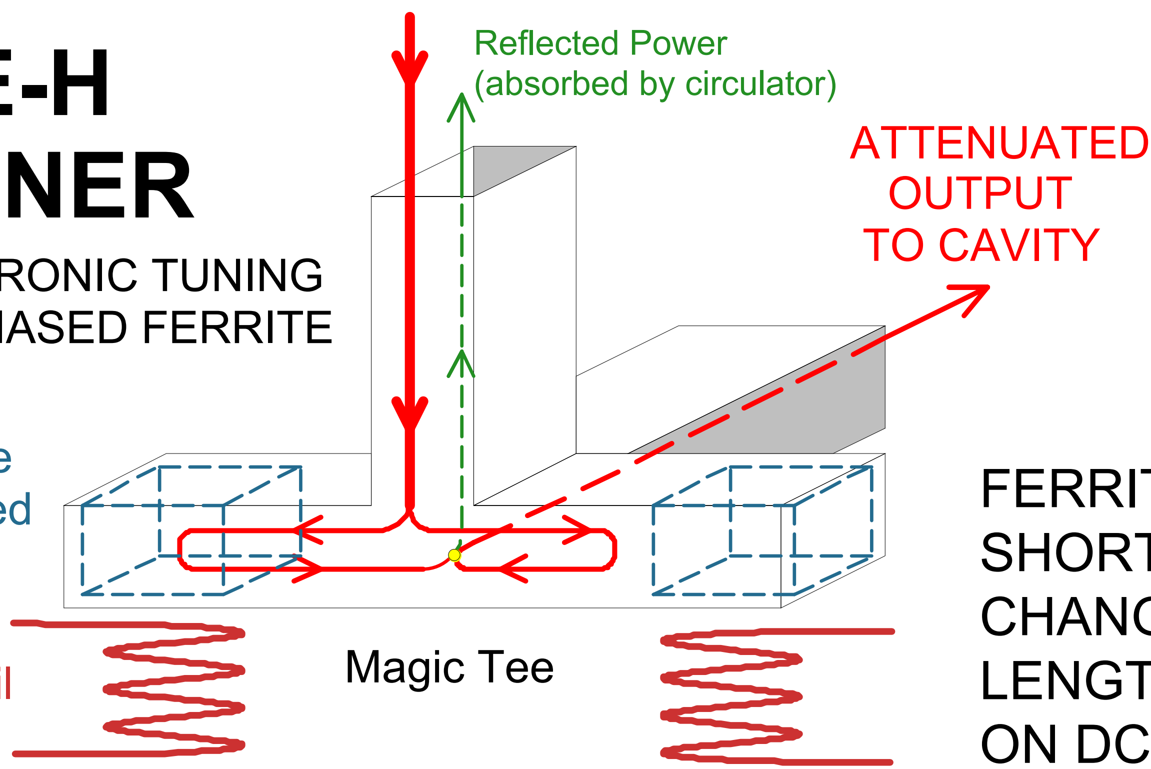
E-H TUNER
- Provides Phase and Amplitude Control for Cavities
- Biased Ferrite Provides Electronic Control

SUPERCONDUCTING RF CAVITY
- Couples RF Power to Beam

ELECTRONICALLY ADJUSTABLE E-H TUNER

E-H TUNER

ELECTRONIC TUNING WITH BIASED FERRITE



Attractive Price Quote from AFT

(<< Klystron)

FERRITE LOADED SHORTED STUBS CHANGE ELECTRICAL LENGTH DEPENDING ON DC MAGNETIC BIAS.

TWO COILS PROVIDE INDEPENDENT ***PHASE AND AMPLITUDE*** CONTROL OF CAVITIES

Cost Optimizations & Options

- **Staging: Extend Klystron Fanout 12:1 → 36:1**
  - Drop beam current, extend pulse width
  - Drop rep. rate & avg. power 2 MW→0.5 MW at 8 GeV
  - Still delivers 2 MW from MI at 120 GeV
- **Consider SCRF Front End (RIA Spokes)**
- **Assume TESLA 800 surface fields will work:**
  - Baseline 5 GeV linac by assuming TESLA 500 gradients,
  - Deliver 8 GeV linac by achieving TESLA 800 gradients.

384 Cavities → 240 cavities ; **Linac Length: 650m → 400**

Frequency Options

1. Standardize on SNS / RIA (805 MHz)
   – Develop “modified TESLA” 1207.5 MHz cavities
   – Develop Modified Multi-Beam Klystron
   – Develop new spoke resonator family if SCRF

2. Standardize on TESLA (1300 MHz)
   – Develop new family of “TESLA-Compatible” beta<1 cavities
   – Already 3 vendors for main MBK
   – Develop new spoke resonator family if SCRF

Main Injector with 8 GeV Linac

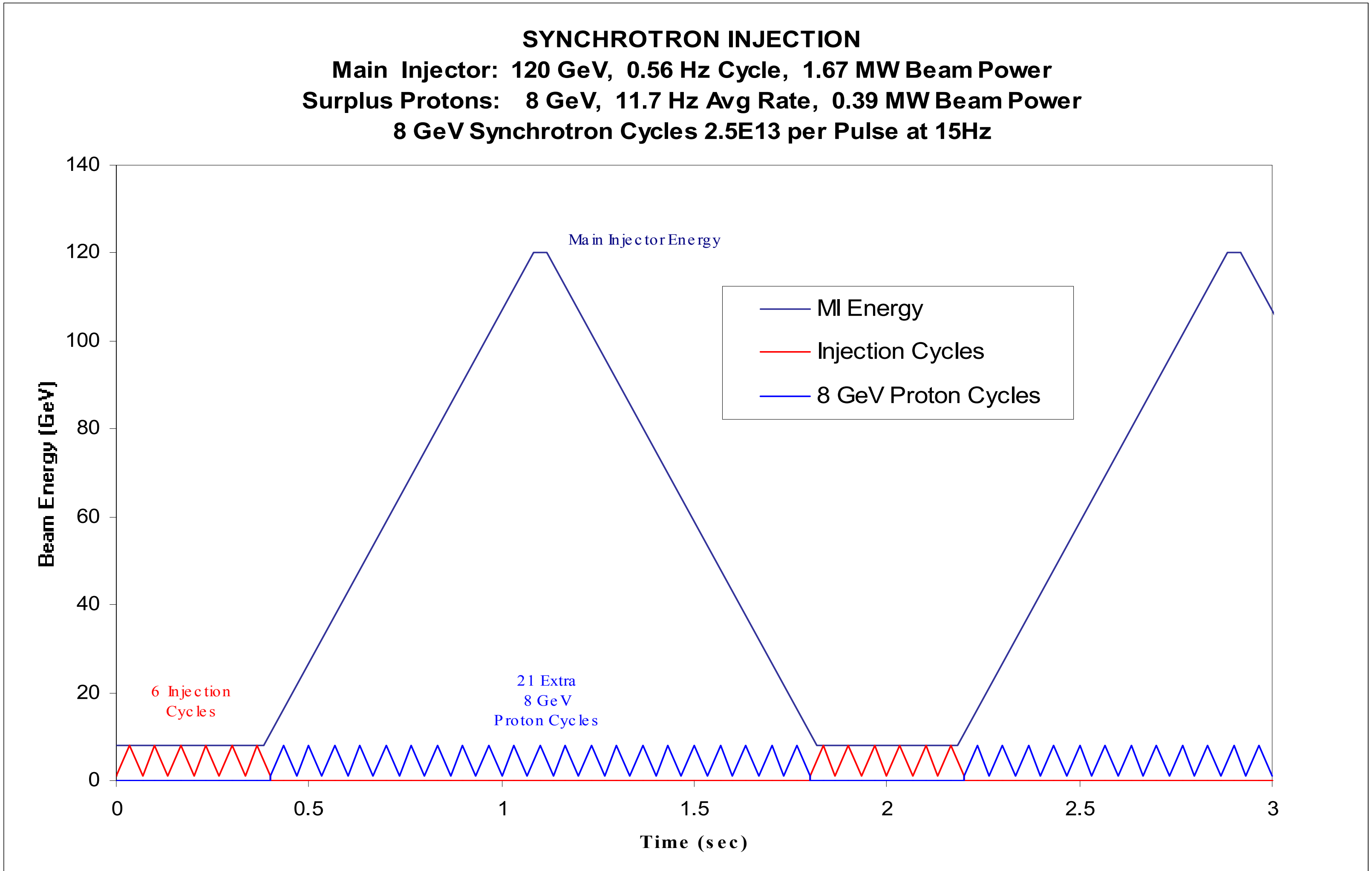
- **H⁻ stripping injection at 8 GeV**
  - 25 mA linac beam current
  - 90-turn Injection gives MI Beam Current ~2.3 A

    (SNS has 1060 turn injection at 1 GeV)
  - preserve linac emittances ~2π (or even ~0.5π (95%) at low currents)
  - phase space painting needed at high currents
  - avoids space charge limitations present at lower energy

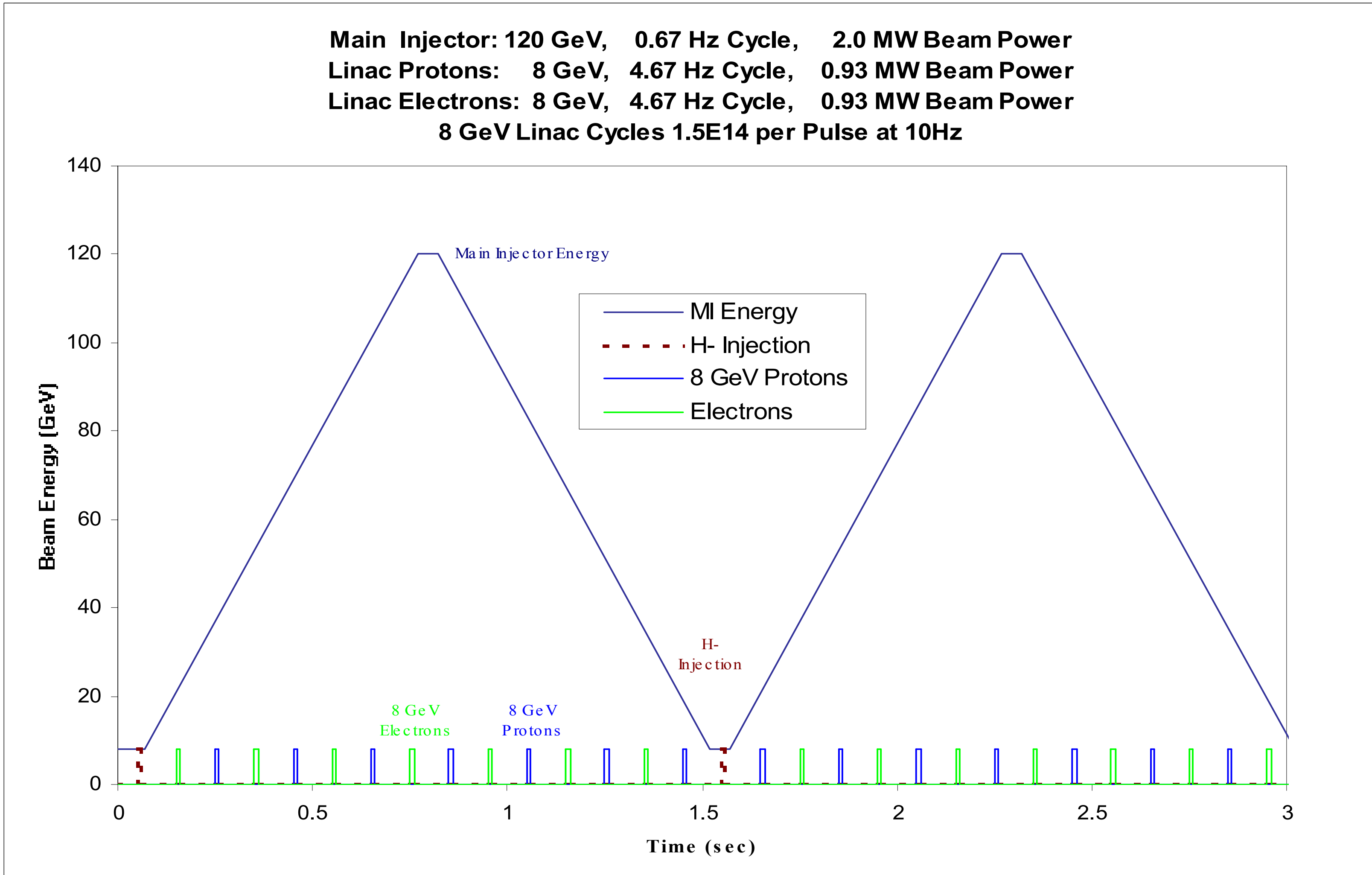
→ ***can put a LOT of beam in MI !***

- **1.5 Second Cycle time to 120 GeV**
  - filling time 1 msec or less
  - no delay for multiple Booster Batches
  - no beam gaps for "Booster Batches" -- only Abort gap
  - Even faster MI cycle times can be considered (x 2 ?)

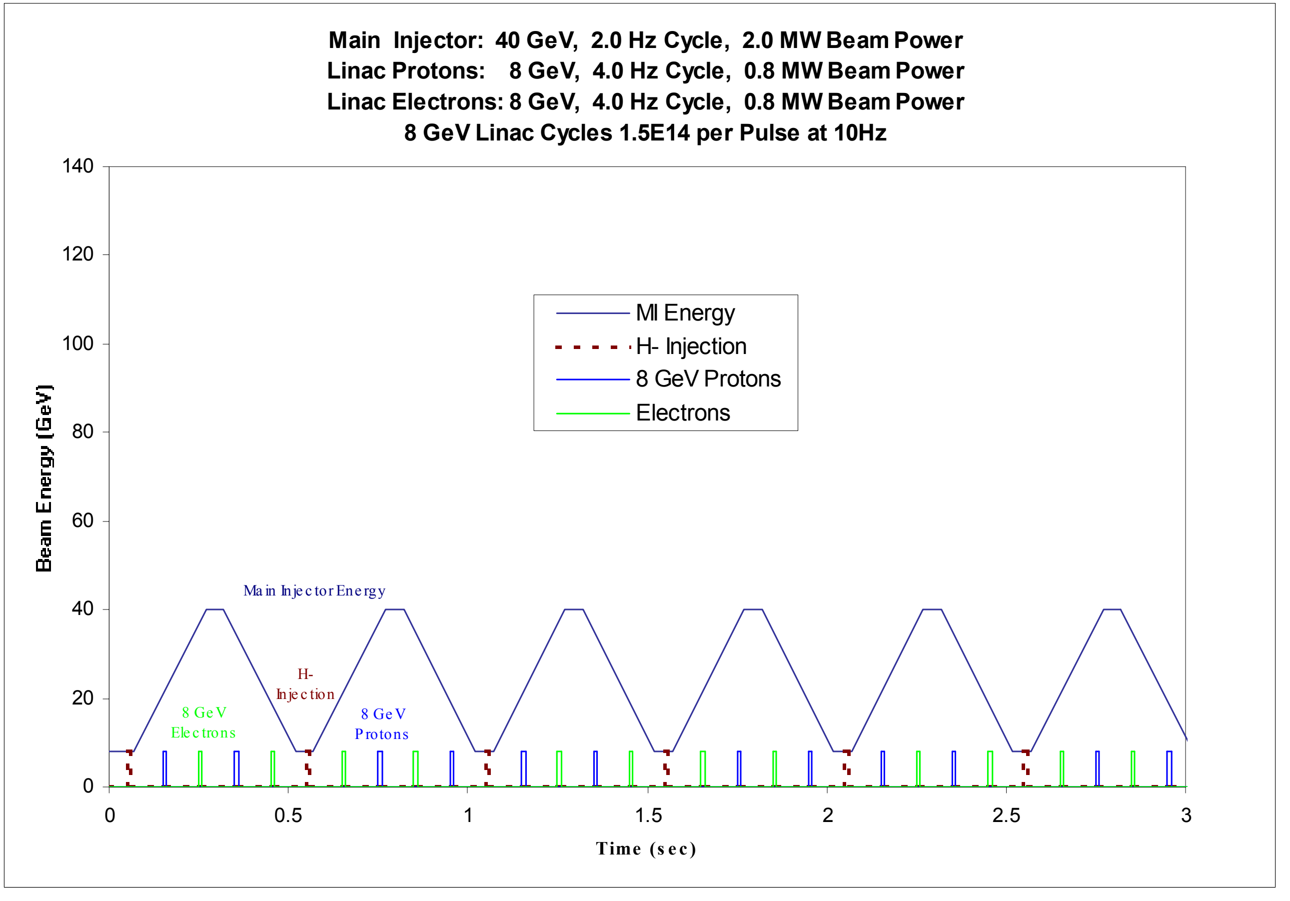
120 GeV Main Injector Cycle with 8 GeV Synchrotron

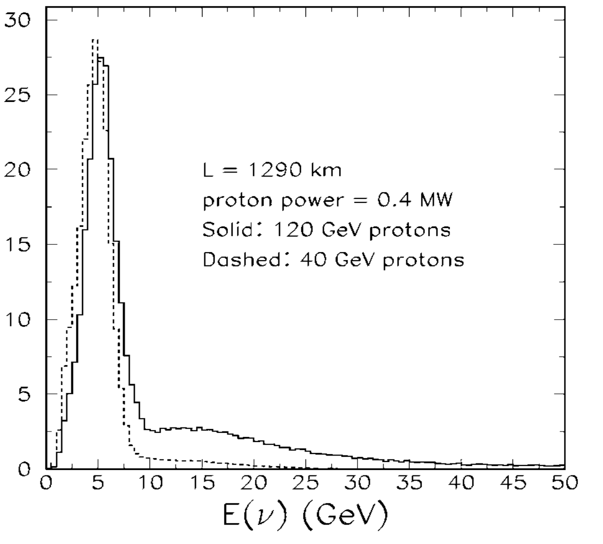


120 GeV Main Injector Cycle with 8 GeV Linac, e- and P



Linac Allows Reduced MI Beam Energy without Compromising Beam Power





- # neutrinos ~ same
- Reduces tail at higher neutrino energies.
- May be a useful operating mode

MI cycles to 40 GeV at 2Hz, retains 2 MW MI beam power

Comparison of PD options

Parameters	Present Proton Source	Proton Driver synchrotron (PD2)	Proton Driver SCRF Linac	Proton Driver SCRF Linac and MI upgrade ?
Linac (Pulse Freq)	5 Hz	15 Hz	10 Hz	10 Hz
Kinetic energy (MeV)	400	600	8000	8000
Peak current (mA)	40	50	28	28
Pulse length (μs)	25	90	1000	1000
Booster (cycles at 15 Hz)				
Extraction kinetic energy (Gev)	8	8	-	-
Protons per cycle	5×10^{12}	2.5×10^{13}	-	-
Protons per hour	9×10^{16} (5 Hz)	1.4×10^{18}	-	-
8 GeV Beam Power (MW)	0.033 (5 Hz)	0.5	2	2
Main Injector				
Extraction Energy for NuMI (Ge	120	120	120	120
Protons per cycle	3×10^{13}	1.5×10^{14}	1.5×10^{14}	1.5 x 1014
fill time (sec)	0.4 (5/15+0.1)	0.4 (5/15+0.1)	0.1	0.1
ramp time (sec)	1.47	1.13	1.4	0.7
cycle time (sec)	1.87	1.53	1.5	0.8
Protons per hour	5.8×10^{16}	3.5×10^{17}	3.5×10^{17}	6.6×10^{17}
Ave Beam Power (MW)	0.3	1.9	1.9	3.6

- **My conclusions: The SCRF Linac PD is more likely to deliver the desired performance, is more "flexible" machine than the synchrotron based PD, and has more "growth" potential**

FLRPC: PD Recommendations

- **We recommend that Fermilab prepare a case sufficient to achieve a statement of mission need (CD-0) for a 2 MW proton source (Proton Driver). We envision this project to be a coordinated combination of upgrades to existing machines and new construction.**
- **We recommend that Fermilab elaborate the physics case for a Proton Driver and develop the design for a superconducting linear accelerator to replace the existing Linac-Booster system. Fermilab should prepare project management documentation including cost & schedule estimates and a plan for the required R&D. Cost & schedule estimates for Proton Driver based on a new booster synchrotron and new linac should be produced for comparison. A Technical Design Report should be prepared for the chosen technology.**

CONCLUSIONS

- **Understanding the physics of neutrino oscillations, the mass hierarchy, and perhaps CP violation in the neutrino sector requires a new generation of long baseline neutrino experiments → a new intense proton source (Proton Driver)**
- **Similar in scope to the Main Injector Project (cost/schedule)**
- **A 8 GeV Synchrotron or a Superconducting Linac appear to be both technically possible. However the SCRF linac has many attractive features if it can be made affordable**
- **The FNAL management has requested (charge) that the 8 GeV linac design be developed including cost & schedule information so that a technology choice can be made.**
- **Documentation in support of establishment of mission need, including both technical design and physics studies, will be produced in the next year.**
- **It is likely this will lead to a request for CD-0 from the DOE**